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Stability investigations in composite steel-concrete walls for restoration purposes to enhance structural and sustainability design

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Abstract. In the present paper a methodology is proposed to evaluate the sustainability of intervention in existing multi-storey concrete buildings using structural steel systems. Taking into account that an intervention in an existing building can be characterized as sustainable if the design considerations include critical sustainability assessments, a method is proposed and then applied to a case study for the restoration of an eight-floor building located at the center of the city ofThessaloniki.This case study is also compared to other relevant assessments with the option of reuse of the existing building only with elementary restoration works and the design of a new composite steel-concrete building constructed at the same location. The analysis includes a description of the building characteristics and pathologies, with an estimation of the structural performance after the application of an optimization process when using structural steel systems for its enhancement.

1. Introduction

Building design has major impact on many of the issues referred to sustainability and it is therefore important engineers to possess methods that help them to deliver sustainable designs [11]. Although, it is rather easy to construct new «green» or «sustainable» buildings, it is much more complex to renovate the existing building stock so that it fulfills sustainability standards. Nevertheless, old buildings are the major consumers of energy and one of the largest sources of greenhouse gas emissions as they are replaced by new buildings only at an extremely low rate. As the demand for green buildings grows, the market of sustainable renovation is gaining strong momentum and it is set to become one of the dominant sectors of the construction industry.About twenty five billion square meters of floor space in the EU and approximately 40 percent of the residential building stock has been built prior to 1960. About 68 percent of the energy consumption in Europe refers to these buildings.

The ability of existing buildings to be rehabilitated and strengthened is an important sustainability issue because due to the low strength and resistance of the old structural members can lead to the extension of their service life. In particular the seismic response of existing multi-storey buildings is the most important issue in seismic areas that should be taken into account in the process of assessing sustainability. Reversibility of the structural steel intervention combined to strength and its ease-of-use offers a wide-range of design possibilities e.g. loading upgrading or extension of the area of the building[6]. In such cases, a variety of reversible steel structures may be designed in order to renovate the building and upgrade its seismic performance, respecting in the meantime the main form and design characteristics of the structure. These design possibilities may be not only necessary for its reuse, but also provides functionality and viability leading to a possible extension of its lifetime.

The present paper aims to highlight first the structural steel and composite (of steel and concrete) systems contribution [5], [7], [9], to existing buildings safety factor increase [12]. This retrofit is necessary to allow for the satisfaction of the design inequality where the load capacity of the structure is greater than or equal to the respective design demand (Capacity ≥ Demand). This design inequality must be satisfied not only in terms of resistance, but also in terms of stiffness [10].The installation of steel braces has been a known method for the seismic strengthening of RC frames in orderto increase the stiffness of the building [1]. Following a similar approach a new innovative prefabricated double-shell composite wall of steel and concrete module exhibiting excellent structural performance, to increase the stiffness of an existing RC building frame system is herein proposed [8].

Figure 1(a). Existing multistorey RC building in the city ofThessaloniki, (case study).

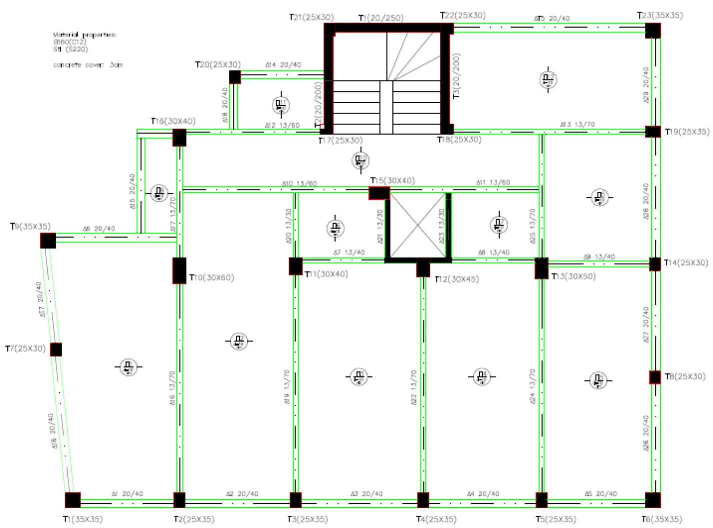

Figure 1(b). Representative floor plan layout of the existing multistorey building (case study).

The method for evaluating the sustainability of restorations in existing RC buildings described above tested on a case study of the restoration design of an eight-floor RC frame building located in the center of the city ofThessaloniki(see figure 1a, 1b). The structural and seismic response of the updated structural system after interventions has been analysed by taking into account two different steel structural systems (cases b.1 and b.2 respectively) under consideration. The first updated structural system (case b.1) included the installation of inverted V steel bracing system on discrete bays of the RC frames of the building. Whilst, the second one (case b.2) included strengthening by the previously mentioned prefabricated steel-concrete composite wall module. Subsequently, both of two cases are compared to other relevant assessments for the option of (a) the reuse of the existing building only with elementary restoration works and (c) the demolition of the existing building and the design of a new composite steel-concrete building that could be constructed in the same location.

Based on the conclusions drawn during the assessment of the structure and the nature, extent and intensity of the damage or deterioration (if any), intervention related decision is made with the aim to meet the basic requirements of the existing seismic code, minimize the cost and serve the social needs. The stock of older buildings in the center of Thessaloniki built before 1985's is many times more than the number of new buildings. 1985 is related with the history of Structural Engineering as the date of a serious change of the Seismic Code in Greece. That was decided after the conclusions made for the safety of buildings of Thessaloniki from the catastrophic earthquake event in 1978.

Currently, the relevant existing regulations for existing concrete buildings in Greece, referring to methods of intervention in buildings only apply to post-earthquake damage and do not include methodologies to increase the capacity of an existing building against seismic hazard. It is therefore important for the engineers to know in terms of sustainability the impact score of applying such a restoration project on existing concrete buildings (decision b.1 or b.2) , in comparison to the aforementioned (a) and (c) possible design decisions.

2. Sustainable indicators

2.1. Sustainability indicators and buildings

Sustainability indicators for buildings are grouped under three generally accepted key themes: environmental protection, society, resistance-economy. The impact of some of these indicators, such as performance level, construction and maintenance cost andlifetime depends on analytical quantity terms. The method of assessment used for other indicators such as those related to aesthetics and cultural heritage is more subjective and involves addressing a series of questions to engineers. The following sections briefly describe the sustainable indicators and their impact assessment.

As far as environmental protection is concerned, climate change indicator represented by carbon dioxide emissions. The steel industry for instance, has made significant reductions in greenhouse gas emissions in the past decades deploying new technologies in steel manufacturing resulting in benefits to the environment and economies. In order to adequate evaluate this indicator, there must be an estimation, if possible, of carbon dioxide equivalent emissions associated with materials for construction and maintenance work, transport of materials from factory gate to building site, plant required for construction and transport of construction and demolition waste. For example, the actual method of calculation in the case study of the eight-floor RC frame building at hand, estimates that on average 1.8 tons of CO_2 emitted for every ton of steel produced. Civil infrastructure, in general, requires significant quantities of resources for construction, use and maintenance. In this global aim to promote energy efficiency, it is important to minimize the energy for manufacture, construction, repair and demolition of building elements, including the transportation of materials to the building site.

Another indicator concerns the amount of hazardous waste and the volume of material going to landfill. The aim here is to reuse or recycle more and more materials, thus reducing the total volume of waste going to landfill. Steel has a major advantage comparing to concrete as a constructive material because it is 100% recyclable.

Society theme includes the indicators of aesthetic and cultural heritage as well as dust, noise and vibrations disturbance. Aesthetics is a qualitative factor based purely on a series of questions concerning the structure as a whole, the structure within its surroundings, serviceability issues and exceptional circumstances. On the other hand, it is essential to examine the control measures in respect of issues like waste disposal, material storage, effects on the neighbours, especially is the case where the construction site is within the build fabric. In any case dust, noise, vibrations are site-related operations that may include blasting and use of heavy equipment. Therefore is aimed to minimize the level and frequency of vibrations, as well as the negative effects on the neighbouring environment.

Last but not least is the key theme of indicators assessment to resistance-economy. Although, an increase in the structural resistance by the seismic redesign is appropriate for existing buildings of seismic-prone areas that designed with low or without seismic hazard. In particular in cases of areas where the seismicity level has been increased by the national authorities designated after their construction or in cases of structures without approved structural design calculations or constructional parts carried out illegally. For serving broader socio-economic needs, various “performance levels”are stipulated under relevant prescribed design earthquakes within a conventional return period. Construction cost includes material cost, labour cost, transportation of materials and workmanship. The construction cost, in any case, remains as one of the most important factors to take final decisions on a project. Civil infrastructure such as multistorey buildings needs a systematic maintenance in order to handle corrosion and other time dependent problems. Estimating the remaining lifetime of a structure is crucial when a decision is to be taken on the rehabilitation or demolition of a structure. The goal of this indicator is to reduce the cost of this routine maintenance and repair work needed over the lifetime of the structure. The aim of the application of this qualitative indicator is to maximize the opportunities for local communities/business. This indicator is assessed by addressing a series of questions concerning the potential impact of a project on local businesses, economy and society.

2.2. Combining impacts

In order to obtain an overall sustainability score, each quantitative factor score is properly combined. There, a problem arises as each indicator is measured in different units. Therefore, in this paper a relative measure of sustainability is proposed rather than an absolute measure. This method is a comparative approach between several other alternative approaches. As the common one being the estimation of the total carbon dioxide.

For instance, the carbon dioxide emissions for three different schemes 1, 2 and 3 are respectively 15000, 16700 and 23000 tons and then the normalized score for scheme 1 is results by adding together the three quantities of the three schemes and then dividing the sum by the number of quantities $[1-15000/(15000+16700+23000)]\cdot 100=72{,}58$. Using this approach, the scheme with the lowest carbon dioxide emissions will score the highest and vice versa. These scores are dimensionless and are comparable with other factors.

The dimensionless scores are multiplied by weighting factors based on the sustainability theme and the number of indicators per theme. The default value for each of the three sustainability themes, environment society and resistance and economics is 1, which gives each theme a weighting of 0,333. Obviously, other weightings may be used if it might be appropriate to place greater emphasis on one schemes over another. Similarly, the default value for all sustainability indicators (energy, dust, costs) is set at 1.

3. Stability of frame members using the innovative steel-concrete composite wall

3.1. Description of the steel-concrete composite wall

A targeted participation and contribution of light - weight composite façade modules to the load frame systems increases the stiffness and decreases the vulnerability of an existing building to seismic loads. The developed elements can be designed to cover the opening of an existing RC frame. In this case the two structural components, existing RC columns andadded composite wall respectively can be interconnected vertically by suitable steel joints and anchors at discrete points and horizontally by anchored shear bars and infusion with concrete in the intermediate gap. The reliability of the applied connections in such a case is based on a series of both experimental and numerical tests that provide clear indications of their limits and durability.

Figure 2. Elementary module of double-shell composite wall on the test bed (real size).

The double-shell wall member in this system is composed of two prefabricated small thickness external concrete walls and a number of internally distributed steel RHS sections. The rest of the gap between the concrete sections is covered by an insulating material (Rockwool boards) of thickness equal with the height of the inside steel section. The two outside concrete panels are attached with full contact to the internal vertical steel hollow sections or to the insulating material (see figure 3). Using this system,the vertical connections where the two elements (RC existing members and added composite system) meet, implemented through steel joints at distinct points and additional steel anchored elements to the existing concrete columns. Moreover, the respective horizontal connections implemented withnew concrete injected into the formed gaps (at the upper and lower end respectively) and special shear connections and anchors. The verification of this structural system to existing RC buildings by more detailed experimental tests in respect with the numerical ones is under the purposes of the immediate future.

3.2. Experimental tests on the stability of the steel-concrete composite wall

The structural performance of an existing concrete building due to the stability of RC frames by adding double-shell composite walls as smart façade elements is an innovative idea under investigation.A targeted participation and contribution of light - weight composite façade modules to the load frame systems increases the stiffness and decreases the vulnerability of an existing building to seismic loads. Moreover, a standard steel connection system has been investigated to connect the composite walls to the adjacent main steel frame elements of the building. The design and verification of this novel steel-concrete composite wall was realized by means of numerical simulation and laboratory testing (see figure 3b). This verification includes the development of an elementary module instead of a whole wall model to investigate in details its structural contribution to the stability of the surrounding frame due to its buckling performance. When using traditional deflection criteria based on the behavior of a single flexural structural member, then the structural performance of the overall wall is on the safe side. The dimensions of this elementary wall module was 700mm widthwith an average height and two rectangular hollow steel sections RHS at the respective width ends.

Figure 3(a). Stability analysis of the steel-concrete composite wall module (numerical model).

Figure 3(b). Characteristic test bed of the stability verification of the steel-concrete composite wall module (real view, scale 1:1).

3.3. Numerical stability evaluation

The effect of buckling resulting from ultimate and seismic design states changes the strength and strain resistance as well as stability response. To evaluate the bearing capability of the structure in the absence of instability phenomena, numerical buckling analysis is at first performed. A unit load is introduced in a simple static analysis coupled to an eigenvalue buckling analysis.This way the load factors are calculated and represent the maximum load the structure can handle before it buckles (see figure 5). Geometric non-linearity because of frictional contact were introduced in the contact surfaces between the rectangular hollow steel sections RHS and the cast concrete.A unit load is introduced in a simple static analysis coupled to an eigenvalue buckling analysis (see figure 3a). This way the load factors are calculated and represent the maximum load the structure can handle before it buckles. The eigenvalue buckling is a linear type of analysis known to produce non-conservative results because of the bifurcation point of buckling, being higher than the actual limit load. This matter can be balanced by introducing safety factors or conducting further non-linear buckling analysis. However, the results of eigenvalue buckling analysis predict the theoretical factors according to classic Euler theory without taking most of the real-world non-linear effects (such as the P-delta effect) under consideration.

To predict behavior of the structural element in buckling as well as the post buckling behavior until failure, two new sets of simulations were proposed.The first set is dedicated in making a conservative prediction of the actual critical load, to make a comparison with the eigenvalue load factors. In that case an external compressive force about 15% of the linear predicted load factor, was applied on top of the element, along with a very small perturbation load in the horizontal direction. The perturbation load is translated to a minimum imperfection in structure, enough to trigger easier the buckling shapes proposed by the linear analysis and to keep the force matrices non-zero.

The second set of simulations utilizes an incremental compressive load, along with a very small perturbation load that increases up to the failure of the structure which is translated as non-convergence in FEA.

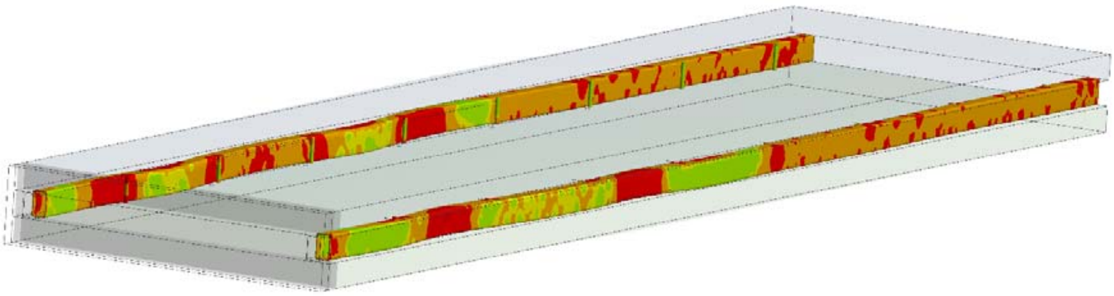

Figure 4. Maximum strain energy of the steel-concrete composite wall module.

During these simulations NLGEOM feature for large deformation is enabled (see figure 4). The time stepping in both simulation sets are set to automatic to predict correctly and accurately the changes in stress, strain and deformation slopes. Comparing the linear eigenvalue analysis and the non-linear analysis there is obvious difference occurring for the bifurcation point. The behavior of the composite double shell wall is easier to understand when examining the structure post-buckling until failure. The concrete shells retain the hollow steel sections on buckling providing extended plasticity of the structure. After the point of 11000kN stress relaxation happens allowing the structure to extend its bearing capability until failure.Buckling analysis in the elastic region of stability, before any yield happens, shows predictable linear behavior for the buckling threshold for the composite structure.

4. Restoration on existing RCmulti-storey buildings using structural steel systems

The innovative restoration on existing RC buildings using structural steel systems, is herein presented by using as an example a real case study. An existing eight-floor RC frame building (see figures 1a), located in the center of the city of Thessaloniki.

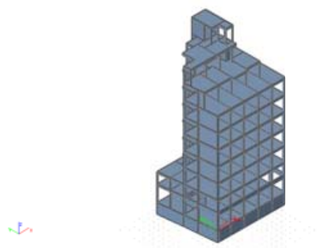

Figure 5a. Numerical FEM model of the existing RC building (case a).

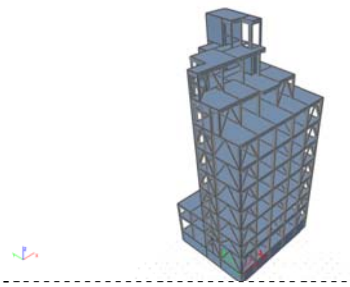

Figure 5b. Numerical FEM model of the strengthened RC building (case b.1)

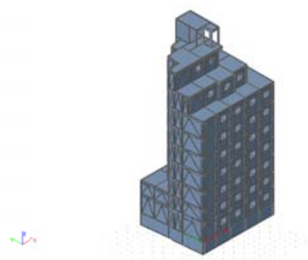

Figure 5c. Numerical FEM model of the strengthened RC building (case b.2)

The seismic response of the structural system before and after interventions is evaluated by taking into account two different steel structural systems (cases b.1 and b.2 respectively) under consideration. The first updated structural system (case b.1) includes the installation of inverted V steel bracing system on discrete bays of the RC frames of the building (see figure 5b), whilst, the second one (case b.2) includes the replacement of all the brick external and main internal walls of the building by the previously mentioned prefabricated steel-concrete composite wall module (see figure 5c). Subsequently, both two cases are compared to the seismic response (case a) of the existing building without strengthening (see figure 5a).

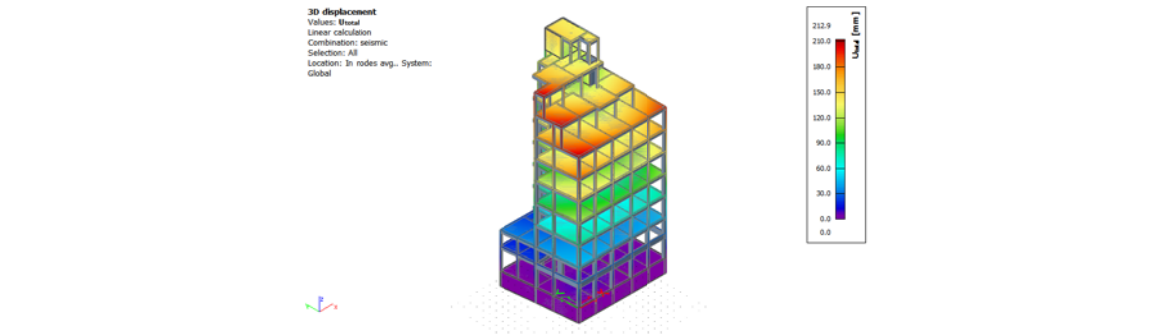

Figure 6a. Displacements distribution (FEM model) of the existing RC building (case a).

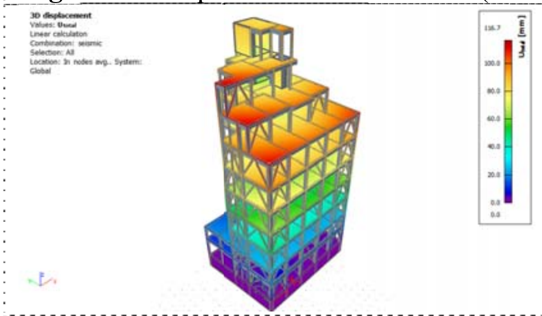

Figure 6b. Displacements reduction (FEM model) due to strengthened of the RC building with inverted V steel bracing system (case b.1)

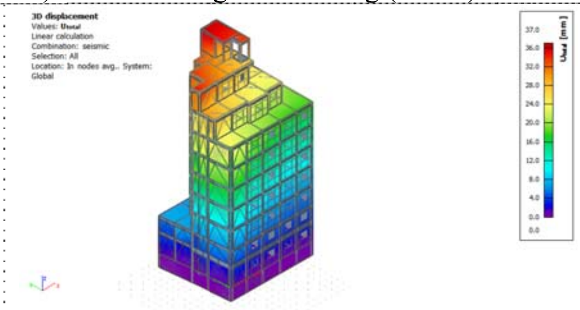

Figure 6c. Displacements reduction (FEM model) due to strengthened of the RC building with prefabricated steel-concrete composite walls (case b.2)

All the described here strengthening procedures satisfy the regulations of E.P.P.O [4] for the case of undamaged buildings, as well as the potential redesign of these existing RC buildings in order to upgrade the level of safety to seismic hazard. For a sustainable restoration design serving broader resistance (social) and economic needs, various “performance levels” (target behaviors) are stipulated under relevant prescribed design earthquake. A nominal technical life equal to the conventional lifetime (actual) of 50 years is generally accepted. Therefore the combination of probability of exceedance of 50% of this lifetime limit (corresponds to an average return period of about 70 years) leads to the performance lever “Immediate Occupancy” (A2). This level is a condition in which it is expected that no building operation is interrupted during and after the design earthquake, with possible exception of minor important functions.Respectively, the combination of probability of exceedance of 10% of this lifetime limit (corresponds to an average return period of about 475 years), leads to the performance lever “Life Safety”(B1). This level is a condition in which repairable damage to the structure is expected to occur during the remaining actual life of the building without causing loss or serious injury of people and without substantial damage to personal property that are stored in the building.

Both applied strengthening techniques using structural steel systems (design cases b.1 and b.2) imply intervention processes which satisfy the “performance levels” A2 and B1 respectively. In any case the intervention strategy aims to improve the seismic behavior of the existing RC building by modifying the basic parameters that affect its seismic resistance.

For the general purposes of this research, elastic dynamic analysis based on the response spectrum method is used in all the design cases under consideration taking into account an adopted behavior factor of q=1.5, which is verified previously by applying a response history analysis (inelastic dynamic analysis), to the structural model of the existing building. In these analyses the maxima of the displacements and internal (axial, bending and shear) forces as well as the spatial superposition of all that quantities, combined according to the relevant provisions of EC8.

It is clear that the reduction of the displacements through strengthening in the building leads to a respective reduction of deformation of resistance members in order to avoid failure. Therefore the comparison of the seismic displacements of the building, resulting from the numerical analysis of each design case is a clear assessment of the "performance" of each option.Thus, it can be seen that the maximum seismic displacement at the top of the building without strengthening (case a)goes up to 220mm, where the "performance levels"A2 and B1 cannot be met (see figure 6a).This result compared with the respective ones a) of the strengthening building with inverted V steel systems (case b.1),where the maximum seismic displacement does not exceed up to 110mm (see figure 6b) and the performance level" A2 is adequate met but the "performance level" B1 is just covered and b) of the strengthening building with steel-concrete composite walls (case b.2),where the maximum seismic displacementis significantly reduce to 40mm (see figure 6c) and both the performance levels" A2 and B1 are adequate met.

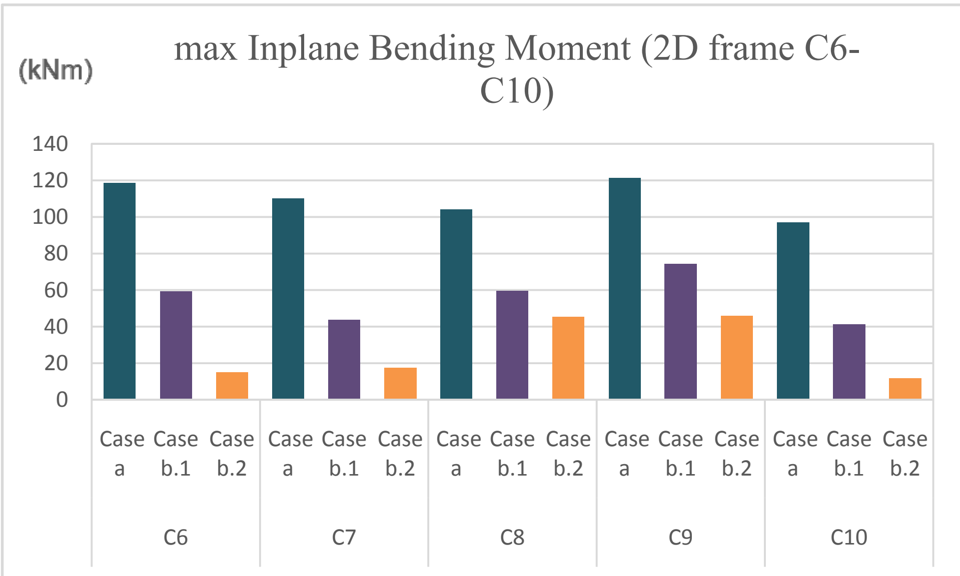

Figure 7. Evaluation of maximum internal bending moment of the existing RC columns under different restoration strategies.

The evaluation of the numerical analysis results between the 3 structural models under consideration shows that both strengthening cases (b.1 and b.2) using steel systems lead to a sustainable design but especially the choice of strengthening with steel-concrete composite walls (case b.2) is optimal (see figure 7).

5. Sustainability Appraisal

According to latest sustainability assessments [2], [3], a well-established methodology is herein applied for appraising the sustainability ofrestoration of existing RC buildings in relation to social key themes. The sustainability indicators in the case of restoration of buildings grouped under the three aforementioned key themes i.e. environmental protection, society and resistance-economy.

INDICATORS	Case a Preservation process Elementary maintenance				Case b.2 Rehabilitation and restoration process Retrofitting by optimal steel systems				Case c Reconstruction process New composite building in the same location			
	Quantity	Norm. score	Weight factor	Weighting score	Quantity	Norm. score	Weight factor	Weighting score	Quantity	Norm. score	Weight factor	Weighting score
ENVIRONMENT												
Climate Change	(kg CO2/y)	46,00	0,111	5,11	(kg CO2/y)	30,00	0,111	3,33	(kg CO2/y)	24,00	0,111	2,66
Resourse Energy	(kWh/y)	30,00	0,111	3,33	(kWh/y)	35,00	0,111	3,89	(kWh/y)	35,00	0,111	3,89
Waste	(kg /y)	46,00	0,111	5,11	(kg /y)	32,50	0,111	3,61	(kg /y)	21,50	0,111	2,39
SOCIETY												
Dust	(kg)	10,00	0,111	1,11	(kg)	60,00	0,111	6,66	(kg)	30,00	0,111	3,33
Noise	(DB)	10,00	0,111	1,11	(DB)	55,00	0,111	6,11	(DB)	40,00	0,111	4,44
Vibrations	(Hz	5,00	0,111	0,56	(Hz	55,00	0,111	6,11	(Hz	40,00	0,111	4,44
RESISTANCE-ECONOMICS												
Performance level	C2	5,00	0,111	0,56	B1/A2	50,00	0,111	5,55	B1/A2	50,00	0,111	5,55
Construction Cost	(€)	46,00	0,111	5,11	(€)	32,50	0,111	3,61	(€)	21,50	0,111	2,39
Lifetime	years	14,50	0,111	1,61	years	33,50	0,111	3,72	years	52,00	0,111	5,77
TOTAL SCORE				23,59				42,57				34,85

Figure 8. Sustainability scores, equal weightings.

The herein proposed method introduces the main sustainability assessments for evaluating and comparing the sustainability impacts of buildings in different construction or restoration strategies. In order to obtain an overall sustainability score, each quantitative factor score have to be combined. There is a problem because each indicator is measured in different units. Therefore, this is a method of relative measure of sustainability rather than an absolute measure because it is a comparative method between alternative approaches.

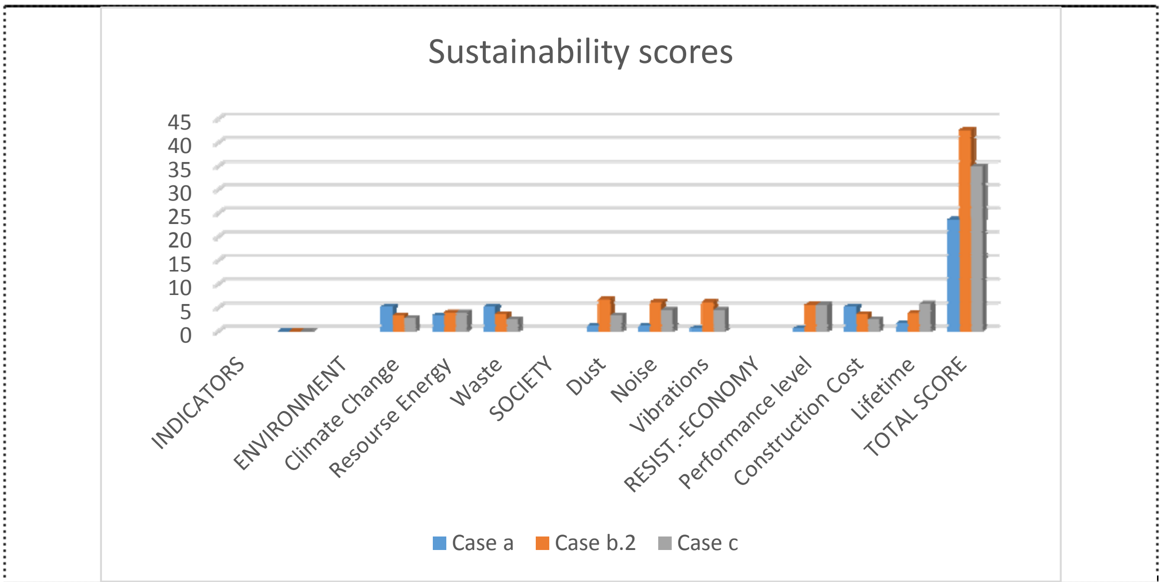

Figure 9. Sustainability appraisal, equal weightings.

The scores of these measures are dimensionless and can be compared with other factors. In this analysis, equal weighting factors are used for all the 3 key themes. The preservation process of the building with elementary maintenance (case a) is compared with the scenario of rehabilitation and restoration process by retrofitting by optimal steel-concrete composite walls (case b.2) and the scenario of reconstruction process, where after a demolition of the existing building a new steel-concrete composite building constructed in the same location (case c). In this analysis first equal weighting factors are used for all the 3 key themes (see figures 8, 9). In this scenario the restoration process using steel-concrete composite walls (case b.2) is the most sustainable solution. In this analysis, equal weighting factors are used for all the 3 key themes, but it is easy to increase the weight of a key theme using unequal weight factors that could be evaluated as more important.

INDICATORS	Case a Preservation process Elementary maintenance				Case b.2 Rehabilitation and restoration process Retrofitting by optimal steel systems				Case c Reconstruction process New composite building in the same location			
	Quantity	Norm. score	Weight factor	Weighting score	Quantity	Norm. score	Weight factor	Weighting score	Quantity	Norm. score	Weight factor	Weighting score
ENVIRONMENT												
Climate Change	(kg CO2/y)	46,00	0,075	3,45	(kg CO2/y)	30,00	0,075	2,25	(kg CO2/y)	24,00	0,075	1,80
Resourse Energy	(kWh/y)	30,00	0,075	2,25	(kWh/y)	35,00	0,075	2,63	(kWh/y)	35,00	0,075	2,63
Waste	(kg /y)	46,00	0,075	3,45	(kg /y)	32,50	0,075	2,44	(kg /y)	21,50	0,075	1,61
SOCIETY												
Dust	(kg)	10,00	0,075	0,75	(kg)	60,00	0,075	4,50	(kg)	30,00	0,075	2,25
Noise	(DB)	10,00	0,075	0,75	(DB)	55,00	0,075	4,13	(DB)	40,00	0,075	3,00
Vibrations	(Hz	5,00	0,075	0,38	(Hz	55,00	0,075	4,13	(Hz	40,00	0,075	3,00
RESISTANCE-ECONOMICS												
Performance level	C2	5,00	0,222	1,11	B1/A2	50,00	0,222	11,10	B1/A2	50,00	0,222	11,10
Construction Cost	(€)	46,00	0,222	10,21	(€)	32,50	0,222	7,22	(€)	21,50	0,222	4,77
Lifetime	years	14,50	0,222	3,22	years	33,50	0,222	7,44	years	52,00	0,222	11,54
TOTAL SCORE				25,57				45,81				41,70

Figure 10. Sustainability scores, unequal weightings.

Therefore, in order to evaluate the reliability of the method, a second scenario is presented with the following assumption: The theme key "Resistance-Economics" is given double weighting of the environmental and society factors (see figures 10, 11).

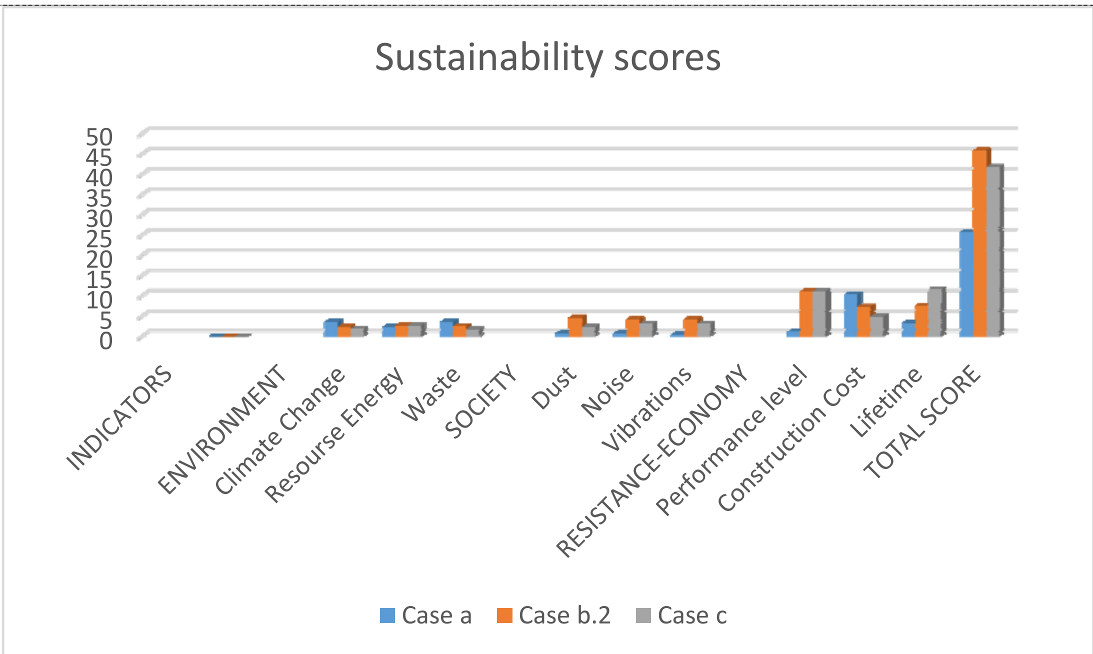

Figure 11. Sustainability appraisal, unequal weightings.

This assumption can be justified by the importance of safety as well as of the total cost of a project in decision making.In this scenario with unequal weight factors, is again the most sustainable solution but with lower score because of the influence of the indicator "lifetime" in the case of constructing of a new building.

6. Conclusions

The sustainable renovation sector offers great potential for environmental protection, job creation, and healthy in-door environment and comfort for its users and therefore, in view of necessity and benefits, there is a strong need to systematically address the evolving field of sustainable renovation of the existing RC buildings.

An intervention strategy using structural steel systems, can improve the seismic behavior of an existing RC building by modifying the basic parameters that affect its seismic resistance.The herein presented strengthening techniques using structural steel systemsimply intervention processes, which satisfy the respective "performance levels" to seismic hazard, according the regulations of Earthquake Planning and Protection Organization of Greece [4].

The verification of the design case to restore an existing RC building by applying steel-concrete composite walls by more detailed laboratory tests is an appropriate condition to obtain a sustainable design solution for the future. This procedure must be combined with additional numerical tests using linear and nonlinear dynamic analysis models to verify the structural performance of the system in detail.

Both qualitative and quantitative factors must be combined to produce a total sustainability score for existing RC buildings but here emphasis is given on the sustainability aspect of resistance and economy due to the importance of seismic hazard.

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